Emulation of Complex Optical Phenomena with Radio Waves: Tailoring Scattering Characteristics with Wire Metamaterial

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Abstract **Tailoring electrodynamical phenomena of radiation, emission, and scattering with auxiliary surrounding structuring is one of primary objectives of fundamental and applied investigations nowadays. Resent interests in optical frequency range are partially related to engineering of light-matter interaction dynamics with applications to invisibility cloaking, quantum information devices, optical interconnects and others. Many of frontier proposals, however, are still at the proof of concept stage and require reliable verifications. While performing and analyzing results of optical experiments are sometimes challenging due to their involved complexity related to nano-scale structuring, experimental platform and fabrication of radio waves devices is relatively straightforward. Being able to emulate a span of optical phenomena with GHz frequencies, we demonstrate the way of tailoring scattering characteristics of objects, embedded in wire metamaterial. Regimes of scattering suppression and super-scattering were investigated and the relations to optical effects were discussed. Furthermore, emulation experiments on other effects, among them the near-field interference, causing directional excitation of waves propagating in hyperbolic metamaterials and invisibility cloaking will be reviewed. The ability to detect both near and far fields at the GHz range opens vast opportunities for emulation experiments of different kinds.**

Index Terms **— Scattering, Antennae, Near-field optics, Purcell Effect, Emission and Radiation.**

I. Introduction

Electromagnetic properties of isolated optical emitters or classical antennas could be substantially different from those, embedded in an environment. For example, directional antennae operation relies on interference between a feeding element and collection of resonant scatterers. Related effects in the optics are usually treated via photonic density of states concept; here the radiation rate enhancement delivered by the presence of a photonic cavity is referred by the name of Purcell effect [1]. However, radiation efficiencies at any spectral range could be described with a unified approach, based on classical electromagnetic Green's functions [2]. Remarkably, quantum description of the emission properties in the weak coupling regime includes the local density of states of states, which is proportional to the imaginary part of classical Green's functions, as the result of the fundamental causality and fluctuation-dissipation relations [2]. This classical-quantum correspondence enables experimental investigations and emulations of complex photonic processes with lower frequencies, where both fabrication and measurements routinely available. This result is the consequence of the Maxwell's equations linearity in the operation frequency.

Here we review our recent progress on emulation studies of complex optical phenomena. In particular, tailoring scattering properties of objects, by embedding them in wire metamaterial medium, will be demonstrated and optical analogues will be drawn. Furthermore, effects of scattering suppression and super-scattering in wire medium, near field interference, and invisibility cloaking will be discussed.

II. Tailoring Scattering with Wire Medium

While the impact of metamaterials on the radiation efficiency is widely studied, the ability to manipulate the electromagnetic scattering properties of embedded objects is less explored. Nevertheless, both of these phenomena are tightly related via the density of electromagnetic states or electromagnetic Green's functions For example, discrete diffraction phenomenon in waveguides arrays utilizes controllably reduced number of available electromagnetic modes for shaping the diffraction pattern - metamaterials exploit similar approach of configuring spatial dependence of modes with additional remarkable flexibility of controlling their density of states.

We have studied the scattering phenomena on objects embedded in a metamaterial assembly (Fig. 1) [3]. In particular, by tailoring electromagnetic properties of the embedding medium, we have shown significant shift of the scattering resonance frequency due to a strong coupling between a scatterer and a metamaterial. Moreover, it has been shown that the direct electric contact between the scatterer and the embedding metamaterial dramatically changes the interaction nature, making it to be conductive instead of the capacitive. Shortage between the wires causes the almost twice stronger effect in terms of the resonance shift. The schematic layout of the experimental sample appears on Fig. 1(a), where the insets demonstrate 'contact' and 'non contact' regimes – scatterer either touches or not the wire medium.

Experimentally obtained RCSs appear on Fig. 1(b) – black dotted line represents the dipole in the free space, while red solid line stays for the scattering inside the metamaterial. The experimental results are in the close correspondence with numerical predictions (the numerical analysis will be discussed in details during the presentation and the large-scale nature of the device will be addressed). Wavy behavior of the free dipole RCS corresponds to oscillations in the

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experimental scattering spectra are due to the artificial Fabry-Perot resonances between wire medium interface and source and receiving horn antennas. Strong scattering suppression at GHz wide spectral window was experimentally observed.

As for a brief comparison, controllable investigation of contact/noncontact regimes between closely situated complex nanostructures is a very challenging task, underlining the strength of the emulation approach. Metamaterials, and wire medium in particular, could create the reduced space for modes, available for wave diffraction and this way manipulate scattering properties of embedded objects. In particular, the creation of reduced diffraction and scattering regimes is beneficial for various applications, including invisibility cloaking [4].

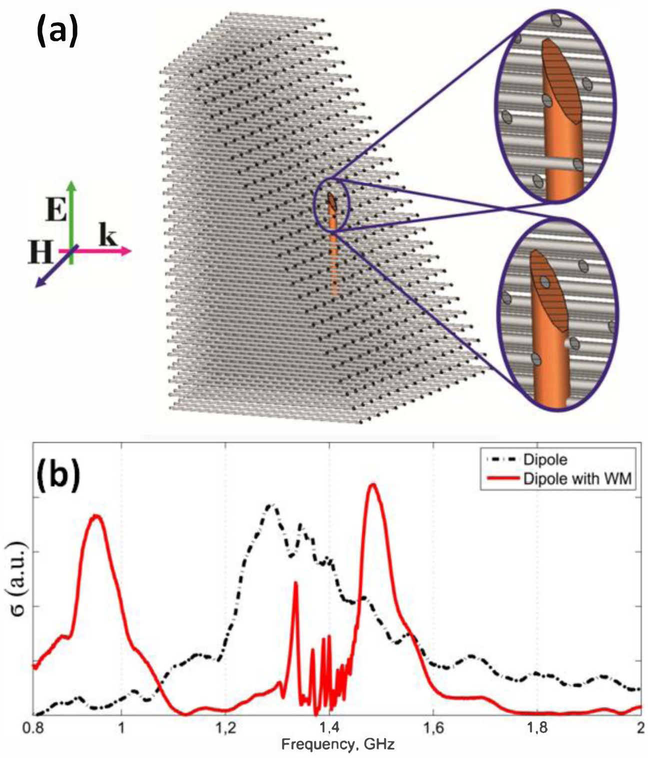

Fig. 1. (a) Schematic layout of the experimental sample. Insets underline two types of interaction regimes – 'contact' (lower inset) and 'non contact' (upper inset). (b) Experimental radar cross-sections (arb. units). Red solid line – 100 mm dipole in 200 mm metamaterial, black dot-dashed line – the same dipole in the free space. The parameters of the wire medium are - 17x26 array of thin metal wires, with diameters equal to 2 mm and length – to 200 mm.

III. Other Emulation experiments

The recently discovered phenomenon of the near-field interference [5] enables routing electromagnetic signals on the nano-scale. The core of the effect is the vectorial type of interaction between circularly polarized emitters and highly confined TM-polarized guided waves. Directionality of the excitation is controlled by polarization handiness of the emitter. However, the direct observation of the effect faces several challenges, related to both fabrication and experimental realization. Furthermore, optical emitters, able to produce well defined circular polarization are rarely present in nature and require special conditions, e.g. cooling and high magnetic fields. On the other hand, obtaining RF antennae, emulating circularly polarized emitter, is relatively straightforward – it could be realized as a pair of perpendicular dipole elements with $\pi/2$ phase shifted feeding currents. The prototype of the setup consist of the near field scanner, excitation probe, and lumped capacitor-inductor array, emulating hyperbolic metamaterial. The experimental evidence of the near-field interference effect was recently reported and will be discussed in details [6].

IV. Conclusions

The set of phenomena, reviewed above, is very challenging for experimental realization in optical domain. However, detailed emulation experiments with microwaves pave a way for advanced investigation, design and proof of concept demonstrations. Several recent achievements in this field will be presented, reviewed and discussed at the conference presentation.

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